

Assessment of Air Quality and Related Values in Shenandoah National Park

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The National Park Service (NPS) is responsible for preserving and protecting air quality and “air quality related values” in the National Park System by ensuring compliance with the requirements of the Clean Air Act, the National Park Service Organic Act, and other pertinent laws, regulations, and policies. This report focuses on the estimated historical, current, and projected future conditions of air quality, acidic deposition, and known air quality related values in Shenandoah National Park—visibility, streams, fish, aquatic insects, soils, and vegetation—and the human-made air pollutants that most affect them.

This technical document was peer-reviewed by internal and external scientists.

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TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	xiii
ACRONYMS	xvii
ACKNOWLEDGMENTS	xxi
EXECUTIVE SUMMARY	xxiii
I. INTRODUCTION	I-1
A. PURPOSE	I-1
B. BACKGROUND	I-2
C. LEGAL RESPONSIBILITIES AND MANAGEMENT POLICIES	I-6
1. National Park Service Organic Act	I-7
2. Enabling Legislation for Shenandoah National Park	I-7
3. Government Performance and Results Act	I-8
4. Clean Air Act	I-10
5. Clean Air Act Implementation Developments	I-14
6. Federal Water Pollution Control (Clean Water) Act	I-17
7. Wilderness Act	I-19
8. Other Pertinent Laws	I-19
9. National Park Service Management Policies	I-21
D. SCOPE	I-22
II. ENVIRONMENTAL SETTING	II-1
A. BACKGROUND	II-1
B. CLIMATE	II-8
C. SCENERY	II-9
D. SURFACE WATERS	II-11
E. AQUATIC BIOTA	II-12
1. Fish	II-12
2. Invertebrates	II-15
F. GEOLOGY AND SOILS	II-16
G. VEGETATION	II-28
H. WILDLIFE	II-33
I. DISTURBANCE	II-34
III. SCIENTIFIC BACKGROUND	III-1
A. PURPOSE	III-1
B. GASEOUS POLLUTANTS	III-1
1. Ground-level Ozone	III-1
2. Sulfur Dioxide	III-3
3. Volatile Organic Compounds and Nitrogen Oxides	III-3
C. ATMOSPHERIC DEPOSITION	III-4

D. AQUATIC RESOURCES AND SENSITIVE INDICATORS	III-6
1. Water Chemistry	III-6
2. Aquatic Fauna	III-12
E. TERRESTRIAL INDICATORS	III-19
1. Plant Symptomatology	III-20
2. Physiological Effects	III-23
3. Nitrogen Saturation and Forest Decline	III-24
4. Soil Acidification	III-27
F. VISIBILITY	III-29
1. Visibility Degradation	III-29
a. Sources of Visibility Degradation	III-29
b. Types of Visibility Degradation	III-30
c. Visibility Scales/Metrics	III-33
2. Background on the Visibility Monitoring Program	III-34
a. Particle Monitoring	III-35
b. Optical Monitoring	III-36
c. View Monitoring	III-36
IV. EMISSIONS AND AIR POLLUTANT TRANSPORT	IV-1
A. PURPOSE	IV-1
B. RECENT AND PROJECTED FUTURE REGIONAL EMISSIONS	IV-1
C. PATTERNS OF AIR POLLUTANT TRANSPORT	IV-12
1. Source Areas	IV-12
2. Airsheds	IV-16
3. Top Five Air Pollutant Source Subregions for Shenandoah National Park	IV-23
4. Relative Contributions by State	IV-24
D. IN-PARK EMISSIONS	IV-28
V. AIR QUALITY AND DEPOSITION	V-1
A. BACKGROUND ON MONITORING EFFORTS	V-1
B. ESTIMATED NATURAL CONDITIONS	V-3
1. Ground-level Ozone	V-3
a. Average Observed Ground-level Ozone Concentrations at Remote Locations	V-4
b. Probability Distribution Methods	V-4
c. Correlation Methods with Ground-level Ozone Precursors	V-5
d. Computer Simulation Modeling	V-6
2. Visibility	V-6
3. Deposition	V-8
C. CURRENT CONDITIONS AND TRENDS	V-10
1. Air Quality	V-10
a. Ambient Conditions	V-10
b. Trends in Air Quality	V-17
c. Ground-level Ozone Formation	V-20
2. Visibility	V-29
a. National Conditions and Trends	V-29
b. Current Conditions and Trends in Shenandoah National Park	V-37

3. Deposition	V-59
a. Ambient Deposition	V-59
b. Trends in Deposition	V-68
D. PROJECTED CHANGES IN FUTURE AIR QUALITY AND DEPOSITION	V-73
VI. ENVIRONMENTAL RECEPTORS AND EFFECTS OF AIR QUALITY	VI-1
A. PURPOSE	VI-1
B. AQUATIC ECOSYSTEMS	VI-1
1. Current Status of Streamwater Chemistry	VI-1
a. Relationships between Geology and Streamwater Chemistry	VI-11
b. Relationships between Soils and Streamwater Chemistry	VI-18
c. Influence of Forest Defoliation on Streamwater Chemistry	VI-22
d. Regional Context	VI-24
2. Trends in Streamwater Chemistry	VI-24
a. Methods and Data	VI-25
b. Results	VI-26
c. Summary of Trends in Streamwater Chemistry in Shenandoah National Park	VI-38
3. Biological Effects	VI-39
a. Acidification Effects on Aquatic Invertebrates in Shenandoah National Park	VI-39
b. Acidification Effects on Fish in Shenandoah National Park	VI-43
4. Episodic Acidification Effects	VI-55
C. VEGETATION	VI-64
1. Effects of Ground-level Ozone and Other Gaseous Pollutants	VI-64
a. Visible Injury Caused by Ground-level Ozone	VI-65
b. Effects of Sulfur and Nitrogen Oxides	VI-67
2. Sensitivity of Plant Species in Shenandoah National Park	VI-67
3. Acidification Effects	VI-70
VII. FUTURE CONDITIONS AND PROGNOSIS FOR RECOVERY	VII-1
A. PURPOSE	VII-1
B. 1990 CLEAN AIR ACT AMENDMENTS AND ALTERNATIVE EMISSIONS CONTROL SCENARIOS	VII-1
C. FUTURE PROJECTIONS	VII-3
1. Aquatic Ecosystems	VII-3
a. Background	VII-3
b. Modeling Methods for Aquatic Effects	VII-4
c. Aquatic Modeling Results	VII-22
d. Implications for Aquatic Biota	VII-43
e. Prognosis for Recovery of Aquatic Ecosystems	VII-64
2. Vegetation	VII-78
a. Background	VII-78
b. Modeling Methods for Ground-level Ozone Effects	VII-78
c. Vegetation Modeling Results	VII-89
d. Prognosis for Recovery of Terrestrial Ecosystems	VII-111
3. Visibility	VII-113

VIII. SUMMARY OF SENSITIVE RECEPTOR IMPACTS AND CONCLUSIONS . . .	VIII-1
A. AQUATIC ECOSYSTEMS	VIII-1
B. TERRESTRIAL ECOSYSTEMS	VIII-2
C. VISIBILITY	VIII-4
D. CONCLUSIONS	VIII-5

IX. REFERENCES	IX-1
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APPENDICES

Appendix A.	Weighting Function for W126 Ground-level Ozone Exposure Index
Appendix B.	Description of Metrics Used to Quantify Visibility Effects
Appendix C.	Description of the Extended RADM Model
Appendix D.	Characteristics of Streams Surveyed within Shenandoah National Park
Appendix E.	Water Chemistry Trends Data
Appendix F.	Description of the MAGIC Model and Application Methods Employed
Appendix G.	Details of TREGRO Parameterization
Appendix H.	Details of Regional Ground-level Ozone Interpolation
Appendix I.	Equations Describing the Simulated Effect of Ground-level Ozone on Vegetative Mass
Appendix J.	Projected Changes in Tree Mass in Response to Ambient Ground-level Ozone Exposure During the Period 1997 to 1999, for Species That Showed Only Minor Response

LIST OF FIGURES

I-1	Locational map for Shenandoah National Park	I-3
II-1	Shenandoah National Park and division into three management districts	II-2
II-2	Location of roads, trails, streams, and scenic historical overlooks within park boundaries	II-3
II-3	Examples of outstanding scenery within Shenandoah National Park	II-10
II-4	Lithologic and geological sensitivity maps of Shenandoah National Park	II-24
II-5	Soils types in Shenandoah National Park	II-29
II-6	Major forest types within Shenandoah National Park, by district	II-30
III-1	Export of base cations from watershed soils	III-27
III-2	Uniform haze, coherent plume, and layered haze: three ways that air pollution can visually degrade a scenic vista	III-31
IV-1	New source permit reviews during the period January 1987 to June 2002	IV-2
IV-2	Bar chart of SO ₂ emissions showing surface and point emissions for the top 10 states in 1990, 1996, and each of the scenarios	IV-8
IV-3	Bar chart of NO _x emissions for surface and point source emissions for the top 10 states in 1990, 1996, and each of the scenarios	IV-9
IV-4	Pie chart of SO ₂ emissions broken down by five source categories comparing 1990, Scenario 3, and Scenario 4	IV-11
IV-5	Pie chart of NO _x emissions by five-source categories comparing 1990 and Scenario 4	IV-13
IV-6	Range of influence of sulfur deposition, oxidized nitrogen deposition, reduced nitrogen deposition, and sulfate air concentrations expressed as the percent contribution from Subregion 20, a 160x160 km square centered at the joining of the state boundaries of WV, KY, and OH in the Ohio River Valley . . .	IV-15
IV-7	Major airsheds for Shenandoah National Park for oxidized nitrogen deposition, sulfur deposition, sulfate air concentrations	IV-18
IV-8	Geographic subdivision of the Shenandoah major airsheds	IV-21
IV-9	Top 5 source regions contributing air pollution in Shenandoah National Park . . .	IV-25
IV-10	First-ranked state percent contribution contour for oxidized nitrogen deposition (VA), sulfur deposition (WV), and sulfate air concentrations (OH)	IV-27
IV-11	In-park Shenandoah National Park emissions relative to emissions from surrounding counties	IV-30
V-1	Estimated natural background particle contributions to visibility reduction in the eastern and western United States	V-9
V-2	Ozone monitoring locations in and near Shenandoah National Park	V-11
V-3	Box and whisker plot showing the monthly maximum 1-hour ozone averages at Big Meadows for the period 1995 to 1997	V-13
V-4	Three-year average of the 4 th highest 8-hour ozone average concentrations	V-14
V-5	Diurnal ozone patterns at Big Meadows during each of the four seasons	V-15
V-6	May-September diurnal ozone patterns at Washington D.C. for the period 1995 to 1999	V-16
V-7	Adjusted SUM06 values for Fauquier County, Frederick County, and Big Meadows monitoring sites for the period 1990 through 2000	V-18
V-8	Adjusted W126 values for Fauquier County, Frederick County, and Big Meadows monitoring sites for the period 1990 through 2000	V-18

V-9	Mean daily ozone production rates during the modeling period in 1995	V-24
V-10	Domain plot of the simulated average VOC loss (L_{VOC}) due to photochemistry . .	V-25
V-11	Simulated values of VPOP, the O_3 production efficiency of VOC photochemistry	V-26
V-12	Sensitivity to added VOC	V-28
V-13	IMPROVE Monitoring Sites	V-30
V-14	Average 3-year visibility (March 1996 - February 1999) reconstructed from IMPROVE aerosol data and represented as extinction coefficient (Mm^{-1}), haziness (deciview), and standard visual range (km)	V-31
V-15	Current visibility impairment expressed in deciviews for the clearest, middle, and haziest 20 percent days based on 1997-1999 IMPROVE data	V-32
V-16	Trends in 75 th percentile visual range over the United States from 1950 through 1994	V-34
V-17	Summary plot of calculated light extinction and the fractional contribution of each species for the 20 monitoring regions in the IMPROVE network	V-36
V-18	Class I area significant trends in haziness for the clearest 20%, middle 20%, and haziest 20% days	V-37
V-19	Class I area significant trends in light extinction due to sulfate for the clearest 20%, middle 20%, and haziest 20% days	V-38
V-20	Fine mass budgets for the mean of the cleanest, middle, and haziest 20% of days for Shenandoah National Park (March 1988 - February 2000)	V-40
V-21	Calculated extinction coefficient budgets for Shenandoah National Park, March 1988-February 2000	V-42
V-22	Monthly contributions of total light extinction contributed by sulfate, nitrate, organics, light absorbing carbon, and soil for Shenandoah National Park (1996 – 1998)	V-43
V-23	Seasonal and annual average calculated extinction for Shenandoah National Park, March 1988 – February 2000	V-44
V-24	Calculated aerosol light extinction in Shenandoah National Park for the cleanest 20%, middle 20%, and haziest 20% of the days in the distribution, February 1988 - March 2000	V-46
V-25	Trends in annual averages for aerosol extinction, standard visual range, and deciview, February 1988 - March 2000	V-47
V-26	Seasonal and annual arithmetic means for transmissometer data (filtered) at Shenandoah National Park during the period 1988 to 2000	V-53
V-27	Seasonal and annual arithmetic means, Shenandoah National Park, nephelometer data, 1996 to 1999	V-55
V-28	Photographs illustrating visibility conditions at Skyland in Shenandoah National Park.	V-57
V-29	Photographs illustrating visibility conditions at Shenandoah National Park, Dickie Ridge vista	V-58
V-30	Annual wet deposition of sulfate throughout the eastern United States during the most recent year of record	V-60
V-31	Annual wet deposition of nitrate throughout the eastern United States during the most recent year of record	V-61
V-32	Annual wet deposition of inorganic nitrogen throughout the eastern United States during the most recent year of record	V-62
V-33	Wet sulfur deposition for the period of record at three monitoring sites in Shenandoah National Park	V-69

V-34	Wet inorganic nitrogen deposition for the period of record at three monitoring sites in Shenandoah National Park	V-70
V-35	Wet ammonium deposition for the period of record at three monitoring sites in Shenandoah National Park	V-71
V-36	Wet nitrate deposition for the period of record at three monitoring sites in Shenandoah National Park	V-72
V-37	Representation of the 80-km grid domain of the RADM model, with the nested 20-km grid that was created for this assessment	V-74
VI-1	Primary study watersheds in Shenandoah National Park shown in relation to the distribution of major bedrock types	VI-2
VI-2	Distribution of streamwater ANC determined in the 1992 spring survey of water chemistry within 11 watersheds in Shenandoah National Park	VI-12
VI-3	Comparison of estimated natural background and current median sulfate concentrations among streams located on major bedrock types in Shenandoah National Park	VI-18
VI-4	Median percent base saturation for soils associated with Shenandoah National Park's three bedrock types	VI-20
VI-5	Median spring ANC of streams in SWAS watersheds during the period 1988 to 1999 versus median base saturation of watershed soils	VI-21
VI-6	Effect of watershed defoliation by the gypsy moth caterpillar on nitrate flux in streamwater	VI-23
VI-7	Trends in solute concentrations for the 14 SWAS streams in Shenandoah National Park	VI-27
VI-8	Median values of annual and seasonal trends in streamwater ANC concentrations among VTSSS and SWAS watersheds: 1988-2001	VI-32
VI-9	Median values of annual and seasonal trends in streamwater SO_4^{2-} concentrations among VTSSS and SWAS watersheds: 1988-2001	VI-33
VI-10	Median values of annual and seasonal trends in streamwater SBC concentrations among VTSSS and SWAS watersheds: 1988-2001	VI-34
VI-11	Life stages of brook trout	VI-36
VI-12	Trends in streamwater SO_4^{2-} concentrations in relation to median SO_4^{2-} concentrations for VTSSS and SWAS streams	VI-37
VI-13	Average number of families of aquatic insects in a sample for each of 14 streams in Shenandoah National Park versus the mean or minimum ANC of each stream	VI-44
VI-14	Average total number of individuals of aquatic insects in a sample for each of 14 streams in Shenandoah National Park versus the mean or minimum ANC of each stream	VI-45
VI-15	Average EPT index in a sample for each of 14 streams in Shenandoah National Park versus the mean or minimum ANC of each stream	VI-46
VI-16	Number of fish species among 13 streams in Shenandoah National Park	VI-50
VI-17	Length-adjusted condition factor, a measure of body size in blacknose dace (<i>Rhinichthys atratulus</i>) among 11 populations in Shenandoah National Park	VI-53
VI-18	Minimum streamwater ANC sampled at each site during each year versus median spring ANC for all samples collected at that site during that spring season	VI-56

VI-19	Relationship between ANC and runoff for streamwater samples collected at intensively-studied sites in Shenandoah National Park	VI-60
VI-20	Decrease in ANC and pH and increase in dissolved aluminum in response to a sharp increase in stream flow in three watersheds within Shenandoah National Park during a hydrological episode in 1995	VI-62
VI-21	Visible injury caused by ozone on milkweed and yellow poplar at Shenandoah National Park	VI-66
VII-1	Calibration results for the MAGIC model, expressed as predicted versus observed values in the calibration year for sulfate, nitrate, sum of base cations, sum of mineral acid anions, calculated ANC, and pH	VII-17
VII-2	Simulated versus observed soils characteristics for modeled watersheds in Shenandoah National Park, expressed as exchangeable Ca, Mg, Na, and K; base saturation; and soil pH	VII-18
VII-3	Simulated versus observed ANC over a ten year period for modeling sites	VII-19
VII-4	MAGIC hindcast projections for modeled sites	VII-23
VII-5	MAGIC model projections of streamwater sulfate under the scenario of constant deposition at 1990 levels and the four emissions control scenarios for modeled sites	VII-27
VII-6	MAGIC model projections of streamwater nitrate under the scenario of constant deposition at 1990 levels and the four emissions control scenarios for modeled sites	VII-30
VII-7	MAGIC model projections of streamwater sum of base cations under the scenario of constant deposition at 1990 levels and the four emissions control scenarios for modeled sites	VII-33
VII-8	MAGIC model projections of streamwater ANC under the scenario of constant deposition at 1990 levels and the four emissions control scenarios for modeled sites	VII-36
VII-9	Predicted and observed number of fish species in 13 Shenandoah National Park streams for the year 2000	VII-45
VII-10	Projected number of fish species in 14 Shenandoah National Park streams for past and present conditions	VII-45
VII-11	Projected number of fish species in 14 Shenandoah National Park streams for the year 2040 in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-48
VII-12	Predicted and observed brook trout categories in 14 Shenandoah National Park streams for 1988-1992	VII-49
VII-13	Projected brook trout categories in 14 Shenandoah National Park streams for past and present conditions	VII-50
VII-14	Projected brook trout categories in 14 Shenandoah National Park streams for the year 2040 in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-51
VII-15	Projected condition factor for blacknose dace and observed presence/absence of blacknose dace in 13 Shenandoah National Park streams for the year 2000 . .	VII-54
VII-16	Projected condition factor for blacknose dace in 14 Shenandoah National Park streams for past and present conditions	VII-55

VII-17	Projected condition factor for blacknose dace in 14 Shenandoah National Park streams for the year 2040 in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-58
VII-18	Projected suitability of streamwater pH for, and observed presence/absence of, nine fish species in 13 Shenandoah National Park streams for the year 2000	VII-60
VII-19	Projected suitability of streamwater pH for nine fish species in 14 Shenandoah National Park streams for past and present conditions	VII-61
VII-20	Projected suitability of streamwater pH for nine fish species in 14 Shenandoah National Park streams for the year 2040 in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-62
VII-21	Relationship between the simulated sulfur deposition load and the percent of modeled streams in Shenandoah National Park that have ANC less than or equal to a critical value (0, 20, or 50 $\mu\text{eq/L}$) in three different future years (2020, 2040, 2100)	VII-72
VII-22	Relationship between the simulated sulfur deposition load and the percent of modeled streams in Shenandoah National Park that have ANC less than or equal to a critical value (0, 20, or 50 $\mu\text{eq/L}$), depending on the future year examined (2020, 2040, or 2100)	VII-73
VII-23	Sulfur critical load simulated by the MAGIC model to protect streams in Shenandoah National Park against acidification to ANC below 0, 20 $\mu\text{eq/L}$, and 50 $\mu\text{eq/L}$ by the year 2040, as a function of 1990 ANC and geologic sensitivity class	VII-75
VII-24	Ozone exposures (total for 1997-1999) used in TREGRO simulations	VII-82
VII-25	Ozone exposures (5 month SUM06) for each of the three simulation years	VII-82
VII-26	Percent change, compared to the lowest ozone exposure, in the mass of the total tree, shoot, stem, and root of basswood, black cherry, chestnut oak, red maple, red oak, sugar maple, white ash, and yellow poplar simulated by TREGRO.	VII-90
VII-27	Simulated effects of ozone on the density of trees, total woody biomass, and basal area of the stand, and the growth of major species in the Chestnut Oak forest type as affected by ozone	VII-93
VII-28	Simulated effects of ozone on the density of trees, total woody biomass, and basal area of the stand, and the growth of major species in the Cove Hardwood forest type as affected by ozone	VII-96
VII-29	Simulated effects of ozone on the density of trees, total woody biomass, and basal area of the stand, and the growth of major species in the Yellow Poplar forest type as affected by ozone	VII-98
VII-30	Comparison of the effects of ozone on the basal area of species simulated as individuals over three years versus as a member of a stand over 100 years	VII-100
VII-31	Interpolated ozone exposure for Shenandoah National Park in 1997	VII-102
VII-32	Interpolated ozone exposure for Shenandoah National Park in 1998	VII-103
VII-33	Interpolated ozone exposure for Shenandoah National Park in 1999	VII-104
VII-34	Interpolated total ozone exposure for Shenandoah National Park, 1997-1999	VII-105
VII-35	Projected change in stem and total mass of white ash in response to ozone exposures in 1997-1999	VII-106

VII-36	Projected change in basal area and woody biomass in Cove Hardwood forests in response to ozone over 100 years	VII-107
VII-37	Projected change in basal area and woody biomass in Chestnut Oak forests in response to ozone over 100 years	VII-108
VII-38	Projected change in basal area and woody biomass in Yellow Poplar forests in response to ozone over 100 years	VII-109

LIST OF TABLES

I-1	National Ambient Air Quality Standards published by the U.S. Environmental Protection Agency	I-11
I-2	Prevention of significant deterioration increments	I-13
II-1	Fish species recorded in Shenandoah National Park streams (as of 2002)	II-13
II-2	Total number of invertebrate families of each order present in Shenandoah National Park streams	II-17
II-3	Invertebrate presence in Shenandoah National Park streams	II-18
II-4	Interquartile distribution of pH, cation exchange capacity, and percent base saturation for soil samples collected in Shenandoah National Park study watersheds during the 2000 soil survey	II-27
III-1	Common symptoms of ozone-induced foliar injury	III-21
IV-1	State-level annual emissions totals of SO ₂ for the 1990 Base Case, the 1996 case, and the four scenarios	IV-3
IV-2	State-level annual emissions totals of NO _x for the 1990 Base Case, the 1996 case, and the four scenarios	IV-4
IV-3	Summary of annual SO ₂ and NO _x emissions subdivided into Surface and Point Sources for the 1990 Base, 1996 and the four scenarios	IV-8
IV-4	Summary of the percent changes in annual SO ₂ and NO _x emissions from the 1990 Base Case to 1996 and the four future scenarios for the Surface and Point Source categories	IV-9
IV-5	Characteristics of major airsheds that contribute air pollution to Shenandoah National Park	IV-17
IV-6	1990 emissions for the states nominally covered by the Shenandoah airsheds . . .	IV-20
IV-7	Contributions from geographic subdivisions of Shenandoah National Park major airsheds and efficiency for causing pollution in the park	IV-22
IV-8	Percent of the pollution in Shenandoah National Park explained by accumulating geographic subdivisions of the major airsheds	IV-23
IV-9	Percent of the pollution in Shenandoah National Park explained by state emissions, expressed as the individual state contributions to deposition and atmospheric concentrations	IV-26
IV-10	Shenandoah National Park 1999 emissions summary	IV-28
IV-11	Annual emissions totals from within Shenandoah National Park and comparison with surrounding counties	IV-29
V-1	Visibility, air quality and atmospheric deposition monitoring at Shenandoah National Park	V-1
V-2	Values for the 10 th and 30 th percentile O ₃ measurements at remote inland locations compared with generally comparable data from Shenandoah National Park	V-5
V-3	Estimated natural background particulate concentrations and light extinction	V-7
V-4	Estimates of historical deposition in Shenandoah National Park of sulfur and oxidized nitrogen at five year intervals	V-10
V-5	Three-year averages of annual 4th highest daily maximum 8-hr ozone concentrations and annual exceedances	V-14
V-6	May Through September SUM06 and W126 ozone exposure values, for the period 8AM-8PM, adjusted by percent of data completeness	V-17

V-7	Trends in May through September (8 AM-8 PM) ozone exposure in and around Shenandoah National Park during the period 1990-2000	V-19
V-8	Trends in May through September daily maximum 1-hour average ozone concentration	V-20
V-9	Summary of Class I area extinction trend analysis	V-36
V-10	Measured fine and coarse aerosol mass concentrations for Shenandoah National Park	V-39
V-11	Seasonal and annual average standard visual range and calculated extinction at Shenandoah National Park, March 1988 - February 2000	V-43
V-12	Seasonal and annual arithmetic means, Shenandoah National Park, transmissometer data December 1988 through February 2000	V-50
V-13	Seasonal and annual 20% cleanest visibility metric statistics, Shenandoah National Park, transmissometer data, December 1988 through February 2000 . . .	V-51
V-14	Seasonal and annual 20% haziest visibility metric statistics, Shenandoah National Park, transmissometer data, December 1988 through February 2000 . . .	V-52
V-15	Seasonal and annual arithmetic means, Shenandoah National Park, nephelometer data, 1996 through February 2000	V-54
V-16	Precipitation volume and measured concentrations of major ions in precipitation at monitoring sites within Shenandoah National Park	V-63
V-17	Measured wet deposition fluxes at monitoring sites within Shenandoah National Park	V-65
V-18	Estimated dry deposition fluxes at Big Meadows, based on data and calculations from CASTNet	V-67
V-19	Percent changes in pollutants and pollutant metrics relative to the 1990 Base Case as predicted by the Extended RADM model	V-76
VI-1	Interquartile distributions of ANC, sulfate and sum of base cations for Shenandoah National Park study streams during the period 1988 to 2001	VI-5
VI-2	Bedrock distribution in Shenandoah National Park and SWAS watersheds	VI-10
VI-3	Range and distribution of streamwater concentrations within Shenandoah National Park associated with major bedrock	VI-16
VI-4	Interquartile distribution of pH, cation exchange capacity, and percent base saturation for soil samples collected in Shenandoah National Park study watersheds during the 2000 soil survey	VI-19
VI-5	Interquartile distributions for each bedrock class of pH, cation exchange capacity, and percent base saturation for all soil pits excavated within the 2000 soil survey	VI-22
VI-6	Median trends in solute concentrations within geographically or lithologically defined classes for the 14-year period 1988-2001 (water years)	VI-28
VI-7	Minimum, average and maximum ANC values in the 14 Shenandoah National Park study streams during the period 1988 to 2001 for all quarterly samples	VI-42
VI-8	Critical pH thresholds for fish species of Shenandoah National Park.	VI-47
VI-9	Streamwater acid neutralizing capacity categories for brook trout response	VI-49
VI-10	Median streamwater ANC and watershed area of intensively-studied streams in Shenandoah National Park.	VI-51
VI-11	List of plant species in Shenandoah National Park known to be sensitive to visible injury on foliage from ozone exposure levels found within the park	VI-68

VI-12	Calcium and aluminum data collected for soil water samples from three watersheds in Shenandoah National Park during the period 1999-2000	VI-75
VII-1	Annual deposition of sulfur and nitrogen projected by the Enhanced Regional Acid Deposition Model for the four scenarios	VII-3
VII-2	Five-year average estimates of wet, dry, and total deposition of sulfur and nitrogen, which were used to calibrate the MAGIC model to watersheds modeled in Shenandoah National Park for streamwater chemistry	VII-6
VII-3	Wet and dry deposition input data for Shenandoah National Park sites	VII-9
VII-4	Assignment of historical deposition sequences at Shenandoah National Park, based on ASTRAP modeled deposition	VII-10
VII-5	Percent changes in sulfur and nitrogen deposition relative to 1990 base, calculated for emissions control scenarios	VII-11
VII-6	Streamwater input data for Shenandoah National Park modeling sites	VII-13
VII-7	Soils input data for Shenandoah National Park modeling sites	VII-14
VII-8	ANC in streams within Shenandoah National Park derived from MAGIC simulations for the past, the present, and for selected years in the future	VII-39
VII-9	pH in streams within Shenandoah National Park derived from MAGIC simulations for the past, the present, and for selected years in the future	VII-41
VII-10	Projected number of fish species in streams within Shenandoah National Park estimated from simulations for the past and for the future in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-46
VII-11	Projected brook trout categories in streams within Shenandoah National Park estimated from simulations for the past and for the future in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-52
VII-12	Projected condition factor for blacknose dace in streams within Shenandoah National Park estimated from simulations for the past in response to historical deposition and for the future in response to simulated constant deposition at 1990 levels and the four emissions control scenarios	VII-56
VII-13	Estimated critical load of sulfur to achieve a variety of ANC endpoints in a variety of future years for modeled streams in Shenandoah National Park	VII-69
VII-14	Median and range of estimated critical load values for sulfur deposition, by principal geologic sensitivity class within the watershed	VII-70
VII-15	Estimated percent change in 1990 sulfur deposition required to produce a variety of ANC endpoints in a variety of future years for streams in Shenandoah National Park	VII-71
VII-16	Regression equations for estimating critical load of sulfur deposition to protect against having ANC below a given threshold in a given endpoint year, based on 14 modeled streams in Shenandoah National Park	VII-76
VII-17	Total three-year daylight (0800-2000) ozone exposure metrics calculated from hourly concentrations used for TREGRO simulations	VII-80
VII-18	Twelve-month ozone exposure metrics, by year, calculated from hourly concentrations used for TREGRO simulations	VII-81
VII-19	Modifiers of ZELIG processes calculated from TREGRO simulations	VII-85
VII-20	Species included in three forest types simulated with ZELIG	VII-86
VII-21	Degree of visibility improvement associated with emission reductions scenarios	VII-114

LIST OF ACRONYMS

AERP	Aquatic Effects Research Program
Al	Aluminum
ANC	Acid neutralizing capacity
AQRV	Air quality related value
ARD	Air Resources Division
ASTRAP	Advanced Statistical Trajectory Regional Air Pollution model
BART	Best Available Retrofit Technology
BEA	Bureau of Economic Analysis
C	Carbon
Ca	Calcium
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CARB	California Air Resources Board
CASTNet	Clean Air Status and Trends Network
CEC	Cation exchange capacity
Cl	Chloride
CIRA	Cooperative Institute for Research in the Atmosphere
CO	Carbon monoxide
CPOM	Coarse particulate organic matter
DDF	Dry deposition factor
DOC	Dissolved organic carbon
DOI	U.S. Department of the Interior
DOM	Dissolved organic matter
dv	Deciview
EGU	Electric generating unit
EPA	U.S. Environmental Protection Agency
EPT	Ephemeroptera-Plecoptera-Trichoptera
FIA	Forest Inventory Analysis
FISH	Fish in Sensitive Habitats Project
FLM	Federal Land Manager
FMP	Fisheries Management Plan
FPOM	Fine particulate organic matter
GIS	Geographic Information System
GPRA	Government Performance and Results Act
GRSM	Great Smoky Mountains National Park
HAP	Hazardous Air Pollutant
HBEF	Hubbard Brook Experimental Forest
HDDV	Heavy Duty Diesel Vehicle
IFS	Integrated Forest Study
IMPROVE	Interagency Monitoring of Protected Visual Environments Program
IPM	Integrated Planning Model
LAC	Light absorbing carbon
LTEMS	Long-Term Ecological Monitoring System
L _{VOC}	Average simulated VOC loss due to photochemistry
MACA	Mammoth Cave National Park

MAGIC	Model of Acidification of Groundwater in Catchments
MAQSIP	Multiscale Air Quality Simulation Platform model
MOU	Memorandum of Understanding
MVCP	Maximum VOC capacity point, the point at which further addition of VOCs reduced ozone concentration
N	Nitrogen
NAAQS	National ambient air quality standards
NADP	National Atmospheric Deposition Program
NADP/NTN	National Atmospheric Deposition Program/National Trends Network
NAPAP	National Acid Precipitation Assessment Program
NAS	National Academy of Sciences
NEI	National Emissions Inventory
NH ₃	Ammonia
NH ₄	Ammonium
NO ₂	Nitrogen dioxide
NO ₃	Nitrate
NO _x	Nitrogen oxides
NO _y	Reactive oxides of nitrogen
NPS	National Park Service
NWS	National Weather Service
O ₃	Ozone
OTC	Ozone Transport Commission
PAN	Peroxyacetylnitrate
P _{O3}	Mean daily total ozone production through photochemical reactions
PO ₄	Phosphate
POM	Particulate organic matter
ppb	Parts per billion
ppbv	Parts per billion by volume
ppm	Parts per million
PSD	Prevention of significant deterioration
RADM	Regional Acid Deposition Model
RHR	Regional Haze Rule
S	Sulfur
SAMAB	Southern Appalachian Man and the Biosphere program
SAMI	Southern Appalachian Mountains Initiative
SBC	Sum of base cations
SHEN	Shenandoah National Park
SIP	State Implementation Plan
SKT	Seasonal Kendal Test
SO ₂	Sulfur dioxide
SO ₄	Sulfate
SO _x	Sulfur oxide
SUM06	Sum of all hourly ozone concentrations that are greater than or equal to 0.06 parts per million
SVR	Standard visual range
SWAS	Shenandoah Watershed Study
TMDL	Total maximum daily load

USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VDGIF	Virginia Department of Game and Inland Fisheries
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VPOP	Ozone production per unit of VOC consumed
VR	Visual range
VTSSS	Virginia Trout Stream Sensitivity Study
W126	Sum of all hourly ozone concentrations, where each is weighted by a function that gives greater emphasis to the higher concentrations

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EXECUTIVE SUMMARY

Introduction

Shenandoah National Park overlies the crest of the northern Blue Ridge Mountains of Virginia. The park has one of the most comprehensive air quality monitoring and research programs of all national parks and wilderness areas that are afforded special protection under the Clean Air Act. Under the Clean Air Act (as amended), the Assistant Secretary for Fish, Wildlife and Parks (acting through the park Superintendent) has an “affirmative responsibility” to protect air quality related values from the adverse effects of human-made air pollution.

The park’s air-related science program has emphasized particulate matter, gaseous pollutants, acidic deposition, visibility, and the acid-base status of streams. Over 20 years of monitoring and research show that, despite some recent improvements, the park’s sensitive scenic and aquatic resources remain degraded by human-made air pollution. Furthermore, the park’s air quality does not currently meet the 8-hour ground-level ozone standard set by the U.S. Environmental Protection Agency to protect public health and welfare.

In the late 1990s, park managers determined the need for a comprehensive, state-of-the-science assessment of the park’s air quality and related values in support of air-related regional, state, and park planning, policy-making, permit review, and scientific and outreach activities. This report provides that assessment as well as key resource information. The National Park Service assembled a team of scientists to evaluate the estimated historic, current, and projected future status of air quality and air pollution effects on sensitive resources in the park. This assessment addresses the park’s known air quality related values, including visibility, vegetation, soils, streamwater chemistry, fish, and aquatic insects, as well as the human-made air pollutants that most affect them. This report also summarizes pertinent national and park-specific laws and policies, and describes the park’s current and estimated historic air quality and resource conditions. It synthesizes knowledge on the visibility and ecological effects of atmospheric pollutants, and documents park-specific critical load ranges for the effects of sulfur deposition on surface waters and ground-level ozone on tree growth, forest growth, and species composition. It also projects future air quality, acidic deposition, and resource conditions and recovery, assuming implementation of four emissions control scenarios.

The atmospheric and deposition modeling described herein was conducted using the Extended Regional Acid Deposition Model to: (1) determine principal emissions source

subregions, known as airsheds, responsible for the majority of acidic deposition and sulfate haze affecting the park; (2) apportion the relative contribution of the airshed emissions, as a function of distance from the park, to the acidic deposition and sulfate air concentrations in the park; (3) define the top-ranked source subregions within the airsheds responsible for the largest fraction of acidic deposition and sulfate air concentrations affecting the park; (4) illustrate the relative contributions of 13 eastern states to acidic deposition and sulfate haze in the park; and (5) project future air quality and acidic deposition in response to the emissions control scenarios considered. Park and regional monitoring data were used to characterize recent and current conditions and to evaluate model performance. Four emissions control scenarios were considered. Scenarios 1 and 2 were based on emissions regulations required by the 1990 Clean Air Act Amendments and projected to 2010 and 2020, respectively. Scenario 3 was based on more stringent controls on sulfur dioxide and nitrogen oxides emissions from electric utilities sources than were mandated by the 1990 Clean Air Act Amendments. Scenario 4 was based on the same emissions controls on electric utilities sources as required by Scenario 3, plus more stringent controls on emissions from industrial point sources and mobile sources than required by the 1990 Clean Air Act Amendments.

Dose-response calculations and simulation modeling were used to estimate potential future changes in the extent of damage to visibility, aquatic, and forest resources in Shenandoah National Park in response to Scenarios 1 through 4. The Model of Acidification of Groundwater in Catchments was used to simulate aquatic ecosystem effects and determine ranges of critical sulfur deposition loadings. The TREGRO model was used to simulate the isolated effects of ground-level ozone on tree growth. The ZELIG gap succession model was used to simulate the isolated effects of ozone on forest stand composition and growth. Future visibility conditions were projected for each of the emissions control scenarios on the basis of expected reductions in fine sulfate particle concentrations in the atmosphere and the known contribution of each particle type to light extinction. These analyses augmented a broader literature review pertinent to the effects of human-made air pollutants on visibility and aquatic and terrestrial ecosystems.

Overall, this assessment found that implementation of emissions controls, especially Scenarios 3 and 4, would be expected to make progress toward, but not fully restore, the park's estimated natural visibility conditions and acid-base chemistry of the most sensitive aquatic ecosystems. Full implementation of the 1990 Clean Air Act Amendments (Scenario 2) should also make substantial progress toward protecting park forests from the isolated effects of ground-

level ozone. In addition, thirteen eastern states and several source subregions were identified that can contribute the most toward restoring and protecting air quality and related values in Shenandoah National Park. The following is a summary of key assessment findings by major topic.

Detailed Summary of Assessment Findings

Emissions and Air Pollutant Transport

- Major emissions source subregions impacting the park are found in the Ohio River Valley, northeastern West Virginia, southwestern Pennsylvania, and central and eastern Virginia.
- In descending order of importance, Ohio, Virginia, West Virginia, Pennsylvania, and Kentucky comprise the top five of thirteen key states causing sulfate air concentration and haze impacts at the park. West Virginia, Ohio, Virginia, Pennsylvania, and Kentucky comprise the top five states causing sulfur deposition impacts at the park. Virginia, West Virginia, Ohio, Pennsylvania, and North Carolina comprise the top five states causing oxidized nitrogen deposition impacts at the park.
- Emission sources within about 200 kilometers (125 miles) cause greater visibility and acidic deposition impacts at the park, *on a per ton basis*, than more distant sources.
- Because of the non-linear production of sulfur pollutants during transport, changes in sulfur dioxide emissions do not translate into proportionate changes in sulfate air concentrations or sulfur deposition. These non-linearity effects are more pronounced for haze than deposition, especially at higher sulfate air concentrations.
- For five air pollutants (sulfur dioxide, nitrogen oxides, volatile organic compounds, carbon monoxide, coarse particulate matter), in-park emissions comprise less than 1% of total human-made emissions from the eight counties encompassing the park.

Ambient Air Quality and Acidic Deposition

The park has among the highest monitored concentrations of airborne sulfate particles, acidic deposition, and ground-level ozone of all national parks.

Ground-level Ozone

- Many experts consider 25 parts per million-hour (ppm-hr SUM06) to be an important ozone exposure threshold above which vegetation begins to show effects. The mean and maximum ozone exposures at Big Meadows were 47 ppm-hr and 87 ppm-hr, respectively, during the period 1990-2000.

- The park's air quality from 1997 through 2001 did not meet the 8-hour ground-level ozone standard set in 1997 by the U.S. Environmental Protection Agency to protect public health and welfare.

Acidic Deposition

- Estimated total (wet + dry) annual deposition values at Big Meadows are currently about 13 kg/ha/yr for sulfur and 8 kg/ha/yr for nitrogen.
- The park does not routinely monitor cloud and fog deposition, but limited in-park research suggests its contribution toward the total deposition budget is relatively small compared to higher elevation sites such as Whitetop Mountain, Virginia.
- Concentrations of sulfur in wet deposition have shown a decreasing trend over the past 15 to 20 years at Big Meadows, North Fork Dry Run and White Oak Run.
- Concentrations of nitrogen in wet deposition have shown evidence of some decline over the past 15 to 20 years at North Fork Dry Run and White Oak Run, but not at Big Meadows.

Visibility Status and Trends

Visibility has been degraded in the park, potentially detracting from visitor enjoyment of numerous vistas accessible from Skyline Drive (a Virginia State Scenic Highway), the Appalachian National Scenic Trail, and other trails and points in the park.

- Current annual average visual range is about 20% of the park's estimated natural visual range of approximately 185 kilometers (115 miles).
- Current annual average haziness is about three times greater than the park's estimated natural haziness of about 7.5 deciviews.
- Seasonal variability in visibility is driven primarily by changes in the atmospheric concentration of ammonium sulfate, and poorest visibility occurs in summer.
- Even the park's clearest 20% of days, which occur mainly in winter, are degraded by human-made particulate matter. The fine mass budget on these clearest days includes about 51% sulfates and 12% nitrates.
- Although the clearest 20% of days showed no consistent trend for March 1988 through February 2000, the haziest 20% showed a moderately improving trend.

Terrestrial Ecosystem Status and Trends

Ground-level Ozone

Ground-level ozone is considered to be a long-term, potentially debilitating stress to the park's ozone-sensitive vegetation that can interact with other, potentially exacerbating stresses such as drought, insects, and diseases. This assessment focuses on the isolated effects of ozone on trees and forests. Ground-level ozone also causes visible foliar damage to several plant species in the park, including but not limited to milkweed, black cherry, yellow poplar, and white ash. However, little is known about the relationship between visible foliar injury and the growth or vitality of sensitive plant species.

- Responses of eight tree species to the isolated effects of ground-level ozone exposures were simulated, and ranked in order from most to least sensitive to growth and species composition impacts:

White ash>Basswood=Chestnut oak>Red maple>Yellow poplar>Black cherry=Red oak>Sugar maple.

- Simulations suggested that white ash is more sensitive to growth and species composition impacts than other species, both as an individual and as a component of a forest stand. Ambient ground-level ozone exposure caused an estimated 1% decrease in total growth of white ash, a long-lived species, over the three year simulation period.

Acidic Deposition

Sulfur retention in watershed soils reduces the potential for the acidification of surface waters because it decreases the mobility of sulfate. However, as the finite adsorption capacity of soils is exhausted, sulfate concentration can increase in soil waters and surface waters, potentially contributing to greater acidification. Based on published out-of-park research, it is unlikely that deciduous forest vegetation in the park has experienced sufficiently high deposition of sulfur or nitrogen to cause adverse acidification impacts, although high elevation and isolated coniferous forest areas may be more sensitive.

- The park's recently observed total (wet + dry) nitrogen deposition rates of close to 8 kilograms/hectare/year (kg/ha/yr) are approaching the 10 kg/ha/yr levels observed elsewhere to often be associated with nitrate leaching (an indicator of nitrogen saturation).
- Data from the 2000 soil survey of 14 park watersheds indicated that median base saturation (a reflection of soil acid-base status) was less than 10% for mineral soils associated with siliciclastic bedrock and less than about 14% for mineral soils associated with granitic bedrock in the park. This measure of watershed soil acid-base status is related to the stream's acid neutralizing capacity (ANC). All park watersheds that were characterized by soil base saturation less than about 14% had average streamwater ANC less than 100 microequivalents per liter (µeq/L). Watersheds that had higher soil base

saturation were dominated by the basaltic bedrock type and had average streamwater ANC greater than 100 $\mu\text{eq/L}$.

Aquatic Ecosystem Status and Trends

The acid-base status of the park's streamwater chemistry is closely related to the characteristics of bedrock geology and soils. The park has three major geologic types underlain by siliciclastic (quartzite and sandstone), granitic, and basaltic bedrock. Each of these bedrock types underlies about one-third of the park area. Siliciclastic sites have the greatest sensitivity to acidification, while granitic sites have moderate sensitivity and basaltic sites have low sensitivity. Sulfur is the primary determinant of precipitation acidity and sulfate is the dominant acid anion associated with acidic streams, both in the central Appalachian Mountains region and within the park. Sulfur deposition has acidified park streams and affected in-stream biota, particularly in watersheds dominated by siliciclastic bedrock types that give rise to soils with low base saturation and relatively low sulfur adsorption, and to streams with low ANC. In the absence of severe disturbance such as forest defoliation by the gypsy moth, nitrogen is generally tightly cycled within park watersheds and does not contribute significantly toward streamwater acidification.

- Of the 14 park streams modeled for this assessment, none had simulated pre-industrial streamwater ANC less than 50 $\mu\text{eq/L}$, suggesting that these streams may have supported a greater variety of aquatic fauna.
- Almost half of the siliciclastic streams in a 1992 in-park survey of small subwatersheds were chronically acidic ($\text{ANC} < 0$ $\mu\text{eq/L}$) in which lethal effects on brook trout are probable. The balance of siliciclastic streams had ANC in the episodically acidic range (having chronic ANC between 0 and 20 $\mu\text{eq/L}$) in which sub-lethal or lethal effects are possible. Many of the streams associated with granitic bedrock in this survey were in the indeterminate ANC range (20-50 $\mu\text{eq/L}$) for brook trout. In contrast, the streams associated with basaltic bedrock had relatively high ANC values that were well within the suitable range for brook trout. These thresholds were developed for brook trout, which is considered the most acid tolerant fish species in the park. Species which are more acid-sensitive, such as blacknose dace and some mayfly species, likely have higher suitable ANC ranges than brook trout. Generally, ANC values greater than 20 to 50 $\mu\text{eq/L}$ should support greater diversity and larger populations of aquatic fauna.
- Episodic acidification of park streams can be attributed to acidic deposition and natural processes, and it is superimposed on baseflow chemistry that is more acidic than pre-industrial conditions. Episodic ANC values are generally about 20% lower than baseflow values.
- Acidic episodes in low ANC park streams killed young brook trout and adult blacknose dace in field bioassays.

- Modeling results suggested that park streams that occur on siliciclastic bedrock have generally lost one or two species, and some streams may have lost up to four species, of fish in response to acidic deposition.
- Low ANC park streams generally have lower fish species richness, lower population density, poorer blacknose dace condition, fewer age classes, smaller sizes, and lower field bioassay survival than higher ANC streams.
- Higher ANC streams generally have greater numbers of families and numbers of individuals in each of three important benthic insect orders: mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera) than low-ANC streams.
- Park streamwater chemistry is showing signs of ANC recovery in response to decreased sulfur deposition, whereas streamwater chemistry within the larger western Virginia region is not. Recent changes in both streamwater sulfate concentrations and ANC are generally smaller than in the northeastern United States, are confounded by seasonal differences, and in many cases are not statistically significant.
- Most park streams do not show evidence of ANC recovery in the winter season when the brook trout is present in its early, more acid-sensitive life stages.

Future Conditions and Prognosis for Recovery

Visibility

- Future improvements in annual average visibility projected to result from the emissions control scenarios ranged from 13% to 38% for Scenarios 2 through 4.
- For the summer season, the degree of needed visibility improvement to restore estimated natural background conditions at the park is nearly 85%. Implementation of the most stringent emissions control scenario (4) was forecasted to achieve a 52.4% improvement in average summer-time visibility at the park.

Terrestrial Ecosystems

- 1997 through 1999 ambient ground-level ozone exposures were projected to cause a 50% decrease in white ash species composition in chestnut oak forests projected over the 100-year simulation period.
- Ground-level ozone exposures greater than ambient levels were projected to cause less than 10% decrease in white ash and yellow poplar species composition in cove hardwood forests over 100 years.
- Ground-level ozone exposure scenarios were projected to cause 0 to 3% decrease in growth or species in yellow poplar forests composition over 100 years.

- Model results suggested that the isolated effects of ground-level ozone on growth and composition of park forests should diminish under Scenarios 2 through 4.
- Foliar injury on sensitive vegetation that occurs at lower ground-level ozone exposures (i.e., 10-15 ppm-hr SUM06) should diminish as a forest stress factor under Scenarios 2 through 4. Foliar injury is projected to be rare under Scenario 4, which assumes more than 50% reduction in ozone exposure.
- Modeling results suggested that ground-level ozone exposures about 15% less than 1997 through 1999 ambient levels should protect against isolated changes in white ash growth and species composition in the park's forests.

Aquatic Ecosystems

Model projections of future streamwater ANC in streams on siliciclastic bedrock ranged from simulated changes less than 10 to greater than 40 $\mu\text{eq/L}$ for scenarios 1 through 4.

- In response to substantial reductions in sulfur deposition (Scenario 4), model projections for the year 2100 suggested that park streams on siliciclastic bedrock would likely experience increases of one to two species of fish, improved suitability for brook trout, and improved condition of blacknose dace. However, none of these streams are projected to fully recover the estimated number of fish species lost in the past in response to acidic deposition.
- Levels of continuous future sulfur deposition that were simulated to cause streamwater ANC to change to three specified critical levels (0, 20 and 50 $\mu\text{eq/L}$) ranged from less than zero (not attainable) to several hundred kg/ha/yr, depending on the site, ANC endpoint, and evaluation year. The specified critical levels correspond to general aquatic fauna response categories.
- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from 9 to 15 kg/ha/yr in order to protect against chronic acidity (ANC less than 0) in the year 2100. Lethal effects on brook trout are probable at ANC less than 0.
- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from 6 to 11 kg/ha/yr in order to protect against acidification to ANC of 20 $\mu\text{eq/L}$ in the year 2100. Sub-lethal or lethal episodic effects on brook trout are possible at ANC 0 to 20 $\mu\text{eq/L}$.
- Modeled streams on siliciclastic bedrock showed critical sulfur deposition loads ranging from less than 0 (not attainable in one modeled stream) to 6 kg/ha/yr to protect against acidification to ANC of 50 in the year 2100. Streams having ANC above 50 $\mu\text{eq/L}$ generally support greater diversity and populations of aquatic fauna than do lower ANC streams.

Conclusions

This assessment reveals that the park's visibility and most sensitive aquatic ecosystems have been degraded by human-made air pollution, although there is some evidence of recent improvement, presumably as a result of Clean Air Act implementation. Full recovery of the park's estimated natural visibility conditions and acid-base chemistry of the most sensitive streams would not occur under any of the four emissions control scenarios, although varying degrees of progress would be made. Implementation of the 1990 Clean Air Act Amendments (Scenario 2) should make substantial progress toward or possibly achieve protecting park forests from the isolated effects of ground-level ozone on tree growth, forest growth, and changes in forest species composition. However, model simulations of isolated effects may underestimate ground-level ozone forest effects, since ozone does not act alone. The park's air quality and related values are primarily influenced by emission sources in Great Lakes States, Mid-Atlantic States, Southeastern States, and several key source subregions that transcend state boundaries. These states and subregions can contribute the most through collaborative, intra- and inter-regional efforts toward restoring and protecting clean air, clear views, and healthy aquatic and terrestrial ecosystems in Shenandoah National Park.

